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Engineering Specification

ALIGNMENT REQUIREMENTS FOR THE LHC LOW-BETA TRIPLETS

Abstract

This paper describes the methods used for the initial alignment and the maintenance of the alignment of the low-beta triplets (mainly the three quadrupoles, the DFBX and the TAS).

It defines the interfaces, from the alignment point of view, with the civil engineering, the mechanics, and the space needed for the alignment.

Prepared by :

Hélène Mainaud Durand
helene.mainaud.durand@cern.ch

Checked by :

Jean-Pierre Quesnel
jean-pierre.quesnel@cern.ch

Williame Coosemans
williame.coosemans@cern.ch

Christian Lasseur
christian.lasseur@cern.ch

Approval leader :

Tom Taylor
Tom.Taylor@cern.ch

Circulated to:

F. Butin, O. Bruning, A. Chaneac, G. De Rijk, B. Elliott, C. Fabjan, C. Fischer, C. Hauviller, A. Herve, H. Hilke, B. Jeanneret, J. Kerby, K. Kershaw, D. Lacarrere, L. Leistam, M. Nessi, R. Ostojic, P. Proudlock, P. Pfund, I. Ruehl, N. Siegel, J. Strait, R. Trant, G. Trinquart, E. Tsesmelis, B. Turner, R. Valbuena, R. Veness, A. Verdier, M. Vitasse, W. Witzeling, J. Zbasnik.

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0.1	2002-05-10	All	Submission for approval
1.0	2002-08-02	p1	Modification of the title
		p5	This procedure does not deal with the installation of the magnets. Modification of ref. [20]
		p6	§3.2 F4 reformulated
		p8	table 3.3.4. Term "flexibility" replaced by "flexibility according to the bellows"
		p9, 10	fig. 1, 2 Modification of the labels in the diagrams
		p11	§3.4.3 Modification of the responsibilities
		p14	§3.7 Modification of the responsibilities
			§3.9.1. Jacks requirements corrected
			§3.9.3. Modification of the responsibilities
		p15	§4.3.3 Tolerance clarified
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1. INTRODUCTION

CERN EST-SU group is responsible for the alignment of the inner triplets for the four experiments ATLAS, ALICE, CMS and LHC-B, and more particularly the 3 quadrupoles (Q1, Q2 and Q3), the DFBX and the TAS.

This document describes the methods used for the alignment of the concerned machine elements, and for the maintenance of their alignment. It defines the interfaces, from the alignment point of view, with the civil engineering, the mechanics and the space needed for the alignment.

This procedure does not deal with the installation of these elements.

2. APPLICABLE DOCUMENTS

- [1] LHC-GI-ES-0002 Fiducialisation of LHC Dipole Magnets.
- [2] LHC-TAS-ES-0001 LHC IP1/IP5 Front Quadrupole Absorbers (TAS)
- [3] LHC-DFBX-ES-0100 Inner Triplet Feedboxes, DFBX
- [4] LHC-DFBX-ES-0200 Inner Triplet Feedboxes General Interfaces
- [5] LHC-LQX-ES-0001 Inner Triplet Systems at IR1, 2, 5 and 8
- [6] IR Alignment table (<http://www-ap.fnal.gov/lhc/meetings/workshop99.html>)
- [8] LHC-GI-ES-0001 Alignment Targets
- [9] Drawing LHCGIMSA0007 Reference socket assembly
- [10] LHC-G-ES-0005 LHC tunnel geodetic reference network
- [11] LHC-G-ES-0003 Positioning of the LHC magnets
- [12] LHC-G-ES-0009 The first positioning of the LHC cryo magnets
- [13] LHCGIMSA0014 Surveyor work space
- [14] LHCIR alignment workshop at Fermilab, 4-5 october 99. Alignment of the inner triplets, Quesnel JP.
- [15] LHC-KUPS-EC-0003, change of the diameter and the height of the second SU shafts (point 1)
- [16] LHC-KR-EC-0002, change of the diameter and the height of the second SU shafts (point 5)
- [17] Closed orbit feed-back from low-beta quadrupole movements at LEP, Tecker F., Coosemans W., Marin A., Rybaltchenko K., Wenninger J. (<http://accelconf.web.cern.ch/accelconf/pac97/papers/pdf/7P062.pdf>)
- [18] Minute of the "ALICE install meeting" held on 01/18/02. (<http://est-lea.web.cern.ch/EST-LEA/>)
- [19] ATF-I-EM-0016.Compte Rendu de la 66ème réunion de coordination pour la zone expérimentale d'ATLAS et son infrastructure, 24/01/02.
- [20] LHCLQXA_0005, Cryostat Q1, Q2 § Q3. Alignment target positions.
- [21] C.Lasseur, Alignment of the LHC machine and experiments, presented at the LEMIC, 27/11/2001. (<http://lhc.web.cern.ch/lhc/lemic/lemic.htm>)
- [22] C. Fynbo, G. Stevenson, "Dose studies for the RR, UJ and RE areas", 25 octobre 2000, LHC TCC document. (<http://lhc-radwg.web.cern.ch/LHC-radwg/>)
- [23] A. Marin, "position sensors", presented at the RADWG day, 7/12/2001. (<http://lhc-radwg.web.cern.ch/LHC-radwg/>)
- [24] LHCGITL_0001 Position of deep geodesic references.

- [25] Minute of the TCC meeting TCC2002-02
- [26] doc EDMS n° 343520, "Système de nivellement hydrostatique des triplets internes de IP8, H. MAINAUD DURAND, 29/04/2002
- [27] LHCLQXA_0006, Cryostat Q1, Q2 § Q3. Spacer.
- [28] LHCLQXA_0007, Cryostat Q1, Q2 § Q3. Target holder.
- [29] LHCLQXA_0008, Cryostat Q1, Q2 § Q3. Target left holder.
- [30] LHCLQXA_0009, Cryostat Q1, Q2 § Q3. Target right holder.

3. COMMON ASPECTS FOR THE 4 INSERTION AREAS

3.1. THE GEODETIC REFERENCE NETWORK

A geodetic reference network has been established in the tunnel all around the machine before dismantling of the LEP machine. All the points are sealed in the floor of the tunnel and known in coordinates X, Y and altitude H. These points guarantee a correct absolute position of the elements all along the tunnel.

In addition, eight reference marks will be sealed deep in the floor of the tunnel near each intersection point (one per IP), and 2 around IP5 and IP1. See [24].

According to [10], the accuracy in the determination of the points is the following:

- absolute planimetric accuracy of the points in the middle of each sector: 6 mm (r.m.s.)
- absolute accuracy of the altitude H (2 points on a same diameter for example): 2 mm (r.m.s.)
- relative planimetric accuracy between 3 consecutive points: 0.3 mm (r.m.s.)
- relative accuracy in altitude between 3 consecutive points: 0.1 mm (r.m.s.)

3.2. ALIGNMENT FUNCTIONS

The alignment of the inner triplets in the tunnel is decomposed in several functions:

- F1: the alignment of one inner triplet with respect to the main elements of the corresponding arc and LSS.
- F2: the alignment of the experiment w.r.t. one inner triplet.
- F3: the alignment of one inner triplet with respect to the other inner triplet (left/right side).
- F4: the alignment of the triplets quadrupoles with respect to each other.

3.3. TYPES OF ALIGNMENT

There are 3 types of alignment detailed in this specification:

- first or initial alignment
- maintenance of the alignment, beam on
- maintenance of the alignment, beam off

3.3.1. INITIAL ALIGNMENT

The different phases of the initial alignment regarding the inner triplets are similar to those detailed in [11]:

- determination and maintenance of the reference network
- marking phase
- first positioning of the quadrupoles
- smoothing or final positioning

All these phases have to be performed before the commissioning of the machine.

3.3.1.1. MARKING PHASE

Significant points regarding each element of the inner triplet are drawn on the floor (position of the external supports of the cryostats, interconnection points,...), using the reference points sealed on the floor.

3.3.1.2. FIRST POSITIONING OF THE ELEMENTS

The elements are moved individually to their theoretical position with their jacks using the manual screws, taking the geodetic network as the absolute reference. At this stage, each magnet to be aligned is not connected to its neighbours.

3.3.1.3. SMOOTHING

By this last step, the relative position of the elements is adjusted. This work shall be possible when the cryo magnets are warm or cold, under vacuum or not. This activity does not refer to the geodetic network, as the magnets are considered at their correct absolute position. Only the relative position between magnets is considered, and the measurements are taken on the fiducials, only from magnet to magnet. After a global mean square adjustment of the measurements, the magnets are adjusted on the best curve line calculated with the previous results.

This work is performed during the installation process, after the connections between magnets have been made, when magnets are cold.

3.3.2. MAINTENANCE OF THE ALIGNMENT *BEAM ON*

The maintenance of the alignment *beam on* involves the quadrupoles Q1, Q2 and Q3, equipped with permanent instrumentation. The position of each cryostat is monitored w.r.t. a reference position. When the offset between current and reference position becomes too important, it is possible to take back each cryostat to its reference position, using the motorized jacks located under it, with remote control.

3.3.3. MAINTENANCE OF THE ALIGNMENT *BEAM OFF*

We take into consideration two cases:

- the periodic maintenance of the alignment of the machine
- a complete realignment, due to a UX displacement.

3.3.3.1. Periodic maintenance beam off

This phase is similar to the smoothing phase of the initial alignment: it allows the adjustment of the relative position of each element of the inner triplet. It shall be possible to do this work when the cryo magnets are warm or cold, under vacuum or not and when each magnet is connected to its neighbour. This activity is performed periodically (approximately once a year) after the commissioning of the LHC machine.

3.3.3.2. Complete realignment during maintenance beam off

Such a realignment may need a repositioning of each magnet w.r.t. the geodetic network. According to the displacements to carry out, it shall be possible to do this work when the cryo magnets are warm or cold, under vacuum or not.

Regarding both cases, the final smoothing shall be done when cryo magnets are connected and cold.

3.3.4. STATE OF ELEMENTS DURING ALIGNMENT PHASES

Type of alignment		State of the element			
		Connections to its neighbours	Flexibility according to the bellows	Temperature	Pressure
initial positioning	absolute positioning	Not connected	//	warm	no vacuum
	smoothing	Connected	4mm	cold	vacuum or not
maintenance	beam on	Connected	2mm	cold	vacuum
	beam off	Connected	4mm	cold or warm	vacuum or not

3.4. FIDUCIALS

The fiducials, also called alignment targets, are the points located on the cryostat that provide the material link to the theoretical axis where the beam should cross the element, which is not accessible, and the magnetic plane when it exists.

For each element, a set of fiducials on the outside surface of the cryostats is determined relative to the beam axis and the magnetic plane. It allows the 3D positioning (and the control of the vertical shape) of the magnets. Its position on the cryostat is determined by the mean of geometrical and magnetic measurements. See [1].

Regarding quadrupoles Q1, Q2 and Q3, two sets of fiducials are determined:

- one set of fiducials dedicated to “standard topographical instrumentation”, used during the phases of initial alignment and maintenance *beam off*.
- one set of fiducials dedicated to permanent instrumentation, used for remote control of quadrupoles when beam is on.

3.4.1. QUADRUPOLES OF THE INNER TRIPLETS

3.4.1.1. QUADRUPOLES Q1 AND Q3

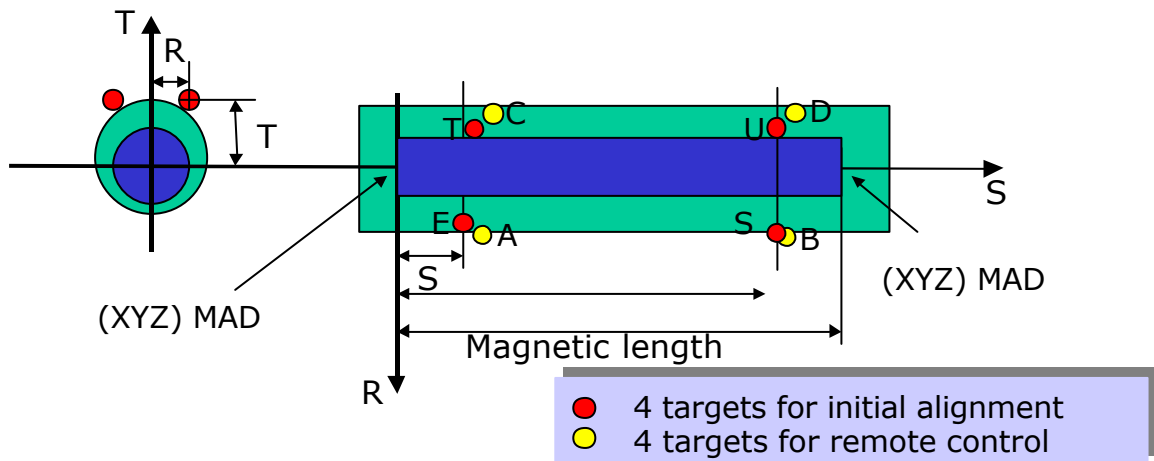
The model of the fiducials is defined by the drawing LHCGIMSA0001. The fiducials are provided by CERN.

On each cryostat, a set of 4 fiducials (named E, T, S and R) is used for the alignment of the elements in the tunnel.

On each cryostat, a set of 4 additional fiducials (named A, B, C and D) is used for supporting the permanent instrumentation which monitor the position of the cryostats.

Normally, 3 fiducials are sufficient for positioning these magnets. Due to the symmetry and the possible location of the magnet in the left or right part of the tunnel, 4 are needed. The targets are located as close as possible to the vertical axis of the jacks to minimize lever arm effects

The theoretical position of the 8 fiducials (i.e. the center of the first sphere on the cup) is calculated on the basis of optics vers. 6.4. with respect to the cold mass in working condition. As it is not planned to adjust the fiducials at their theoretical position, the real values in the 3 directions will be determined by the magnetic measurements.



(XYZ) coordinates are the coordinates calculated by the module Survey of MAD.

3.4.1.2. QUADRUPOLES Q2

The model of the fiducials is defined by the drawing LHC-GIMSA0001. The fiducials are provided by CERN.

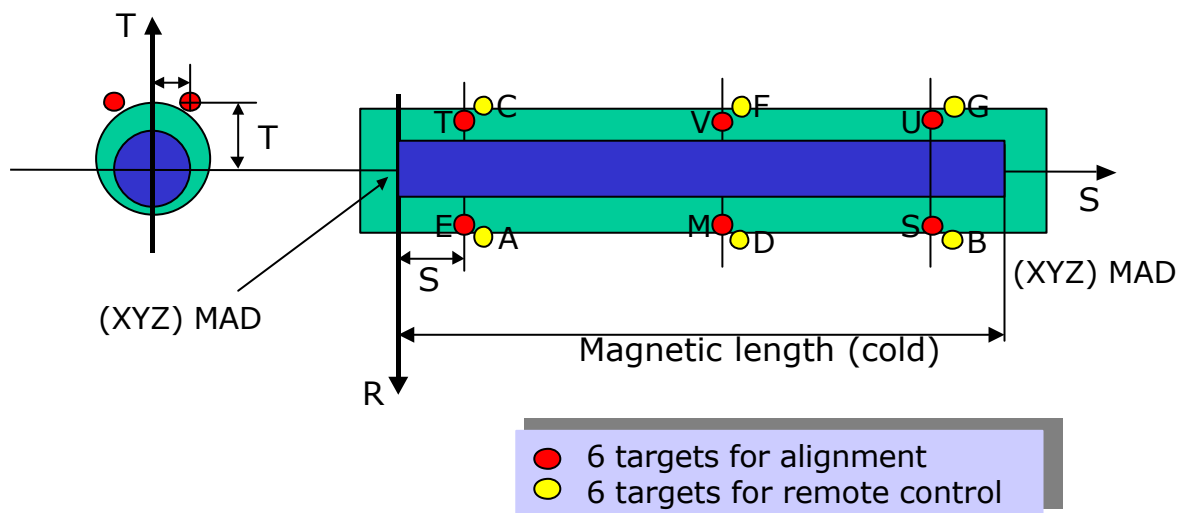
On each quadrupole, a set of 6 fiducials (named E, S, M, T, R and U) is used for the alignment of the elements in the tunnel.

A set of 6 additional fiducials (named A, B, C, D, F and G) is used for supporting the permanent instrumentation which monitors the position of the cryostat.

Normally, as each cryostat Q2 is supported by 4 external jacks, a set of 4 fiducials would have been sufficient. Due to the symmetry and the possible location of the quadrupole as well on left side than on right side in the LHC tunnel, 6 fiducials are needed. The targets are located as close as possible to the vertical axis of the jacks to minimize lever arm effects.

The theoretical position of the 12 fiducials (i.e. the center of the first sphere on the cup) is calculated on the basis on optics vers. 6.4. with respect to the pseudo-cold mass in working condition.

The pseudo-cold mass is defined as a cold mass which would have a length equivalent to the distance between the extreme ends of Q2A and Q2B in MAD (knowing that Q2A and Q2B are housed in one "normal" cold mass). As it is not planned to adjust the fiducials at their theoretical position, the real values will be determined by the magnetic measurements in the 3 directions.



(XYZ) coordinates are the coordinates calculated by the module Survey of MAD.

3.4.2. DFBX

The model of the fiducials is defined by the drawing LHCGIMSA0007. The fiducials are provided by CERN.

The DFBX is equipped with 2 fiducials and a surface reference allowing the control of its transversal tilt (roll angle). The surface reference shall be easily accessible, with free space above. It replaces a third fiducial that would have been hidden by all cables going out the DFBX.

The DFBX is not equipped with fiducials used for remote control.

On each DFBX, the location of the fiducials is the same.

3.4.3. TAS

The TAS is equipped with 4 fiducials mounted on invar rods which penetrate the shielding horizontally and vertically and contact the TAS.

The rods are provided by LBNL.

The fiducials are 1.5" diameter retroreflectors mounted on the rods. These retroreflectors are provided by CERN. See [2].

Around IP1 and IP5, the BPM installed in front of Q1 is fixed mechanically to the TAS, and is aligned consequently when the TAS is aligned. SU will not align independently this BPM, neither measure its position. See [25].

Around IP2 and IP8, the BPM is fixed to the compensator dipoles.

3.4.4. CONSTRAINTS ON THE POSITION OF THE FIDUCIALS

The two sets of fiducials (for "standard" alignment and remote alignment) are not aligned. See layout [20] showing alignment target positions. The set of fiducials used for initial alignment will be equipped with devices like targets, taylor hobson spheres,... Fiducials used for remote control will support sensors and will be linked by stretched wire and hydraulic network which will be in the way if both sets were aligned. Cryostats will be equipped with different alignment target holders, according to the use of the fiducials and their position on the cryostat (left/right). See layouts [27], [28], [29], [30].

All targets used for initial alignment shall be visible from the nearest points of the geodetic network, and workspace allowed for surveyors shall follow example of drawing [20].

It shall be possible to use the first set of fiducials without dismounting the remote control system.

3.4.5. ANCILLARY EQUIPMENT

Instrumentation and other ports on the low-beta triplets and DFBX shall not interfere with space allocated for measurement. For example, regarding the DFBX, the lifting points will have to be removed after installation of the DFBX, because they are in the way of the wire protection.

3.5. THEORETICAL POSITION OF THE ELEMENTS

3.5.1. THEORETICAL POSITIONS ALONG THE BEAM LINE

The theoretical position of the elements is provided by the MAD SURVEY output, which gives the co-ordinates X, Y and Z in the CERN co-ordinates system of the two ends of each element in the working conditions.

For the inner triplets, the magnetic length (cold) of each quadrupole Q1, Q2A, Q2B and Q3 is given w.r.t. the points defined by MAD.

For the DFBX and the TAS, the mechanical length is given.

3.5.2. POSITIONS OF THE FIDUCIALS IN THE TUNNEL

The theoretical positions of the fiducials in the tunnel are computed using the above information and the data which define the position of the fiducials of each cryostat or element.

3.6. POSITION OF THE BPM

The BPMs are not mounted on the cold masses at the time of their completion, but rather after shipment to CERN. The real position of the BPMs with respect to the cold mass will most probably be determined only on the basis of mechanical measurements.

3.7. RESPONSABILITIES

It is the responsibility of the CERN AP group to provide the MAD SURVEY output.

It is the responsibility of FNAL to provide the position of the fiducials on the cryostats of the low-beta triplets, of the LBNL to provide the position of the fiducials on the DFBX, and of the BNL to provide the position of the fiducials on the cryo-dipoles.

It is the responsibility of EST-SU to determine the positions of the fiducials of the TAS with respect to its mechanical references.

It is the responsibility of EST-SU group to calculate the theoretical co-ordinates of the fiducials in the CERN co-ordinates system.

It is the responsibility of CERN to provide the data concerning the position of the PBM with respect to the corresponding fiducials.

3.8. PRECISION OF ALIGNMENT

3.8.1. DEFINITION

The r.m.s. value ($1.\sigma$) of the error of alignment is defined as the square root of the quadratic sum of the r.m.s. value of all the individual errors which can affect the position of the elements on the beam line.

The tolerance is the maximum acceptable error, defined as equal to $3.\sigma$.

The individual errors which compose the errors of alignment are classified into two categories:

- the mechanical errors
- the positioning errors.

The mechanical errors come from:

- the cold mass assembly
- magnetic axis versus mechanical axis
- cold bore tube position inside the cold mass
- the stability in the cryostat of the cold mass when cooling down or warming up
- magnetic measurements when transferring the magnetic axis to the alignment targets

The positioning errors are detailed later in this document.

The final errors of alignment have been defined at the alignment workshop. See [6].

3.8.1.1. THE MECHANICAL ERRORS

These errors are due to the difference between the theoretical models to be built and the real elements built.

The errors in the determination of the position of the fiducials on the cryostats are included in this category.

It is the responsibility of Fermilab to minimise these errors.

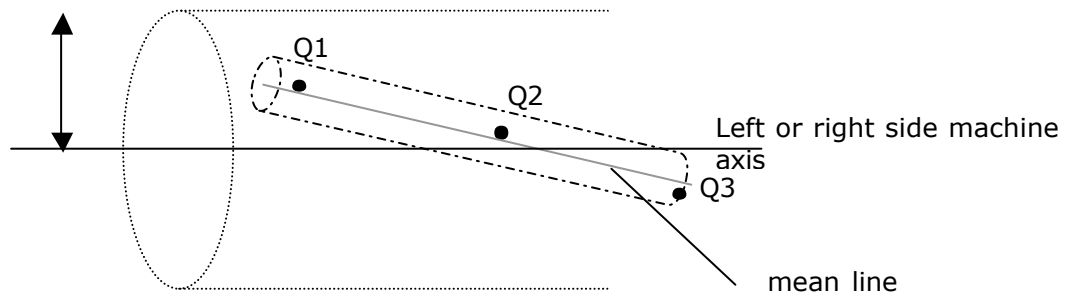
3.8.1.2. THE ERRORS OF POSITIONING IN THE TUNNEL

As the fiducials are the image of the components to be aligned, these errors are the difference between the real position of the fiducials and their theoretical position.

The alignment of the components is under the responsibility of the EST-SU group, so it is its responsibility to minimise these errors.

3.8.2. FINAL ERRORS OF ALIGNMENT FOR THE INNER TRIPLETS

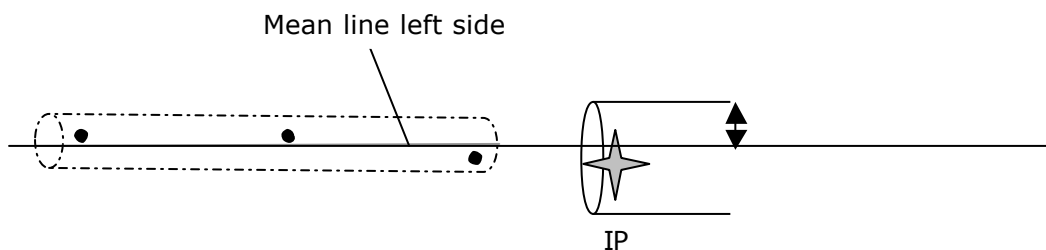
3.8.2.1. FINAL ERRORS OF ALIGNMENT OF ONE TRIPLET W.R.T. THE MAIN ELEMENTS OF THE RING (F1)



The mean line is the regression line calculated with the magnetic centers of Q1, Q2 and Q3. [14]

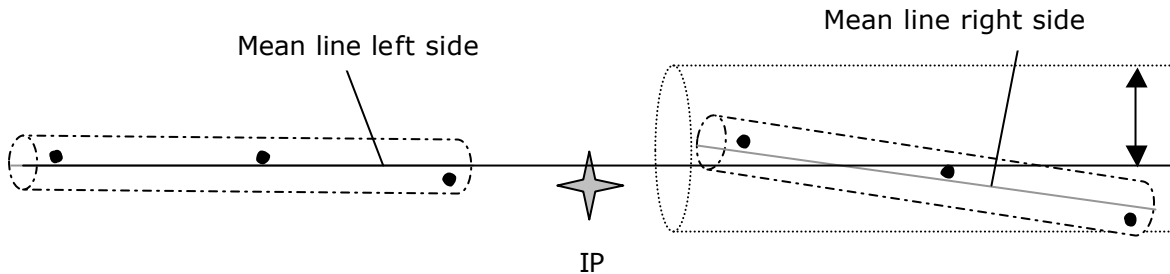
The final error of initial positioning of one triplet w.r.t. the main elements of the ring is roughly equal to the error of the geodetic network determination. See § 3.1.

3.8.2.2. FINAL ERROR OF ALIGNMENT OF THE EXPERIMENT W.R.T. ONE INNER TRIPLET(F2)



Regarding the final errors of positioning of one triplet w.r.t the experiment, see §4.4.

3.8.2.3. FINAL ERROR OF ALIGNMENT OF ONE TRIPLET W.R.T. TO THE OTHER ONE (F3)



Regarding the final error of initial positioning of one triplet w.r.t the other triplet, see § 4.3.4.

Regarding the final error of the maintenance of positioning of one triplet w.r.t. the other triplet, see § 4.5.2.

3.8.2.4. FINAL ERROR OF ALIGNMENT OF THE 3 QUADRUPOLES INSIDE A TRIPLET (F4)

Regarding the final error of positioning one element of the inner triplet, see § 4.3.4. (initial alignment of the quadrupoles, TAS and DFBX), and § 4.5.1. (maintenance of alignment)

3.9. EXTERNAL ADJUSTMENT JACKS

3.9.1. CRYOSTATS Q1, Q2, Q3

It is the responsibility of EST-SU group to provide the external jacks.

The cryostats of Q1 and Q3 are installed on 3 jacks.

The cryostat of Q2 is installed on 4 jacks.

The jacks allow manual and motorized displacements:

- Manual displacements are carried out during initial alignment (absolute positioning and smoothing), and maintenance *beam off*.
 - Resolution (horizontal / vertical axis): < 0.05 mm.
 - Range (horizontal /vertical axis): ± 8 mm.
- Motorized displacements are carried out during maintenance *beam on*.
 - Resolution (horizontal / vertical axis): < 0.01 mm.
 - Range (horizontal / vertical axis): ± 2 mm.

For a total vertical load of 20 tonnes, it is estimated that the jacks must take up to 1 tonne lateral load (per jack) due to the tunnel slope and interconnect reaction.

3.9.2. DFBX

It is the responsibility of CERN-LHC to provide the external jacks for the adjustment of the DFBX.

3.9.3. TAS

It is the responsibility of LBNL to provide the adjustment jacks of the TAS.

4. POINT 1 AND POINT 5 (ATLAS AND CMS AREAS)

4.1. PRINCIPLE

The different tasks achieved by the alignment systems on points 1 and 5 are detailed below:

- Permanent levelling reference for each inner triplet
- Permanent radial reference for each inner triplet
- Permanent vertical and horizontal links (thru UPS galleries) from left to right inner triplet.
- Link with the machine network
- Link with the cavern network

4.2. LINK BETWEEN THE TWO SIDES OF THE MACHINE AROUND THE EXPERIMENT

A correct alignment of the machine elements around the experiments is always a challenge for surveyors. The shielding, the complexity of the areas and the experimental equipment itself block the lines of sight. It has been decided to build parallel galleries to the beam and dedicate to surveying around the two main experiments ATLAS and CMS. A permanent reference line will be installed in this gallery and will cross the experimental area.

The continuity of the geometry in the plane of the machine between the two sides of the experiment is obtained with a permanent *Offset Reference Line* (ORL) installed in the galleries UPS14 and UPS16 at point 1, and the galleries UPS54 and UPS56 at point 5, which crosses the experimental cavern, and an hydrostatic levelling reference network in the vertical plane.

Each gallery is connected to the main tunnel with 2 boreholes (see [15] and [16] showing all drawings references).

The galleries and the boreholes are dedicated in priority for this purpose, and any other use has to be agreed by EST-SU group. The galleries are used as soon as they are under the responsibility of CERN.

Regarding ventilation and access, UPS galleries belong to the cavern system: a gridded gate will be installed between the gallery and the cavern, while gate and boreholes located between the tunnel and the galleries will be airtight.

4.3. INITIAL ALIGNMENT

See § 3.3.1.

4.3.1. INITIAL ALIGNMENT OF QUADRUPOLES Q1, Q2 AND Q3

By the last step of smoothing, the relative position of the magnets is adjusted within an accuracy of 0.1mm (r.m.s.).

4.3.2. INITIAL ALIGNMENT OF THE DFBX

The DFBX are moved individually to their theoretical position with their jacks, taking the geodetic network as the absolute reference. At this stage, each magnet to be aligned is not connected to its neighbours.

As the element is not a critical element for the beam, it is not planned to include a smoothing phase for this element.

4.3.3. ALIGNMENT OF THE TAS

The TAS are aligned and their position controlled from the UX cavern. The 4 fiducials are sighted with a theodolite equipped with a distancemeter standing on a socket point of the UX cavern and are aligned with respect to the mean line of the real position of the inner triplets right and left, within a tolerance of 0.9 mm radially and vertically.

4.3.4. ACCURACY OF THE POSITION OF THE INNER TRIPLET ELEMENTS

According to [14], simulation results for the positioning of the fiducials of the inner triplet elements are:

- radial error: 0.2 mm (r.m.s) from left to right side
- levelling: 0.1 mm (r.m.s).

These results are based on the following hypothesis regarding the precision of the measurements:

- 0.1 mm for distances measurements
- 0.1 mm for wire offsets measurements
- 1 mgon for angles ($1 \text{ gon} = \pi/200 \text{ rad}$)
- a machine considered as perfect (no mechanical errors).

4.4. LINKING THE EXPERIMENT CAVERN TO THE TUNNEL

As seen in § 4.1., the experiment cavern will be linked to the tunnel using a permanent Offset Reference Line and a hydrostatic network, both located in the survey gallery and the UX. But the cryostats of Q1, Q2 and Q3 and their fiducials, which are part of the local geodetic network of the tunnel, will be installed later, after the beginning of the installation of equipment in the caverns. A temporary local geodetic network, composed by tripods located in front of boreholes, will be installed as soon as possible, instead of the cryostats fiducials and will allow the maintenance of the geometry of the cavern from the beginning of the installation up to the end.

Connection measurements between UX cavern and UPS galleries shall be carried out from the UX cavern, with a tacheometer aiming of the reference sockets located on sensors in the UPS galleries. No access to the wire shall be possible in the UX cavern.

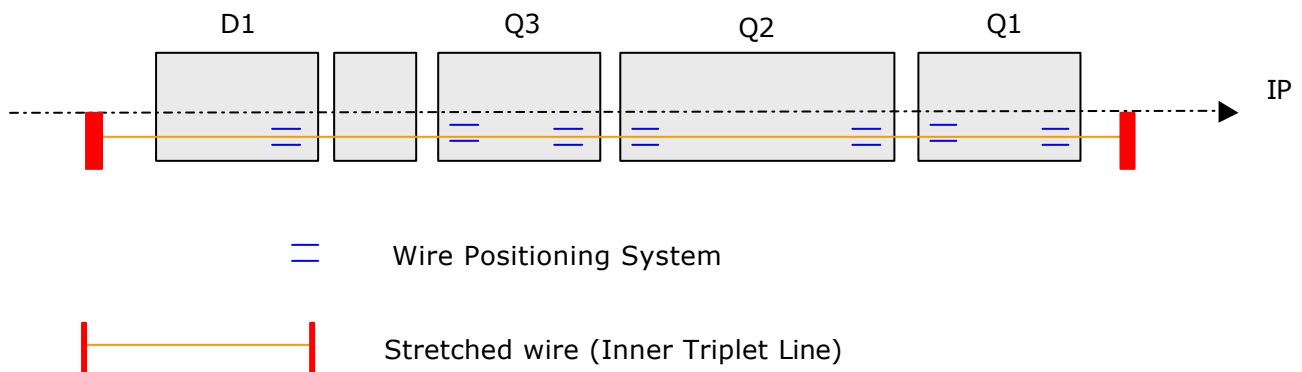
According to a tentative of global "survey" error budget [21], the uncertainty regarding the position of any fiducial mark of the cavern reference network w.r.t. the "machine geometry" is expected to range from 0.5 mm to 1.2 mm r.m.s.

4.5. MAINTENANCE OF THE ALIGNMENT *BEAM ON*

4.5.1. THE REMOTE CONTROL OF ONE INNER TRIPLET

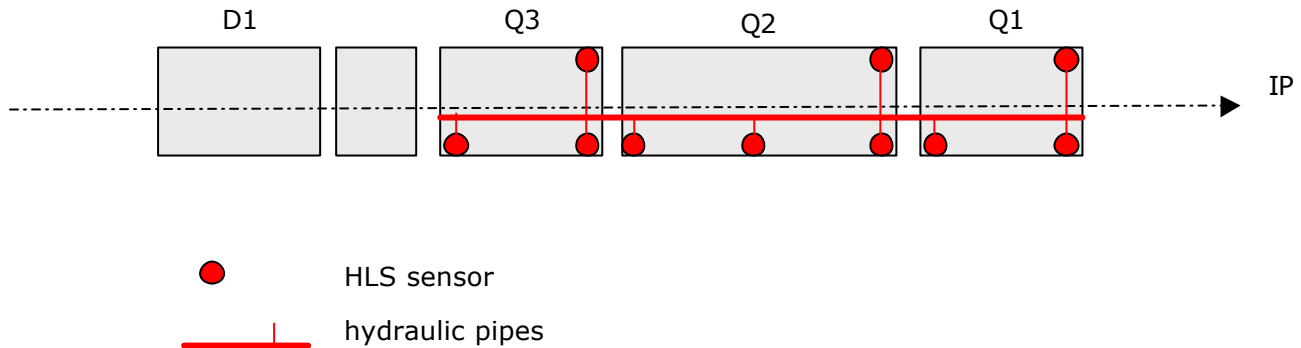
4.5.1.1. PRINCIPLE

The radial position of the quadrupoles of one inner triplet is controlled with a wire stretched between D1 and Q1 and considered as reference. The wire is fixed with a constant tension on elements that are independent from the quadrupoles to control. This line is called the Inner Triplet Line (ITL). The wire sensors (WPS) are plugged to the fiducials dedicated to the remote control and located on the passage side of the cryostat.



The vertical position and the transversal tilt (roll angle) are controlled with the Hydrostatic Levelling System. All the fiducials dedicated to the remote control are equipped with a HLS sensor.

The same system was already used in the LEP around the four interaction points. [17]



On the drawing [20] is shown the space needed for the permanent alignment system and the “traditional” geodetic instruments on each magnet of the inner triplet.

4.5.1.2. POSITIONING ERRORS EXPECTED

In case of a “pleasant environment”, i.e. with no vibrations, no radiation fluences, no magnetic fields,... sensors measuring relative displacements have the following specifications:

Wire Positioning System (WPS)

- Measurement range: ± 5 mm
- Resolution: < 1 μm
- Uncertainty of measurement w.r.t the wire: ± 3 $\mu\text{m} + 1$ $\mu\text{m} / \text{month}$

Hydrostatic Levelling System (HLS)

- Measurement range: 2.5 mm // 10 mm
- Resolution: < 1 μm
- Uncertainty of measurement w.r.t. the water surface: ± 3 $\mu\text{m} + 1$ $\mu\text{m}/\text{month}$

In the tunnel, the sensors won't be in a such environment: important radiation doses are expected. See [22]. This will lead to install sensors with remote electronics (distance of cables between 20-30 m). Such distances of cables will increase significantly the noise of the measurements. Studies are in course regarding uncertainty of measurements of sensors with remote electronics and damages expected due to the radiation doses. See [23].

All racks and remote electronics will be located in UPS galleries.

4.5.2. THE RELATIVE POSITIONING OF THE TWO INNER TRIPLETS

In the horizontal plane, both Inner Triplet Line (ITL) on left and right side are linked continuously to the same Offset Reference Line (ORL) by 6 invar rod devices measuring the distance between ITL and ORL with sensors. The Offset Reference Line is a stretched wire of more than 126 m long, crossing UPS galleries and experiment cavern. See Appendix [B].

In the vertical plane, a hydrostatic network crossing UPS galleries and experiment cavern links the two networks installed on each inner triplet. See Appendix [A].

Both references (the stretched wire following the slope of the tunnel *contained in a square tube of 100x100*, and the water surface (horizontal!) *contained in a 110 diameter tube*) have been integrated in ATLAS and CMS cavern layouts. See layouts [19].

4.6. MAINTENANCE BEAM OFF

The connection between the local network of the inner triplets and the arcs is measured periodically during shutdowns if needed.

This work consists in extending the wire offset measurements or the levelling measurements made on the fiducials of the arc cryomagnets up to Q1 magnet, using the fiducials dedicated for manual measurements, and to include the remote control measurements in the calculations.

5. POINT 2 AND POINT 8 (ALICE AND LHCb)

5.1. PRINCIPLE

The different tasks achieved by the alignment systems on points 2 and 8 are detailed below:

- Permanent levelling reference for each inner triplet
- Permanent radial reference for each inner triplet
- Permanent vertical (threw UPS galleries) from left to right inner triplet.
- Link with the machine network
- Link with the cavern network.

There will not be a permanent radial link between left and right side of the cavern.

5.2. LINK BETWEEN THE TWO SIDES OF THE TUNNEL AROUND THE EXPERIMENT

During the assembly of the experimental detector, links between the right and the left side of the tunnel shall be performed as far as the equipments do not cut the direct line of sight in the UX cavern. The geodetic reference network of the UX cavern for the metrology of the detector is linked in the same time to the tunnel reference network.

After the first alignment of the elements, this network is only used for evaluating the local stability of the tunnel, and the geodetic reference is considered to be based on the fiducials of the elements themselves.

An identical configuration to point 1 and point 5 is installed for the levelling network. Locally, a permanent hydraulic levelling system is installed from Q3 left to Q3 right through the main tunnel and the UX cavern.

Boreholes through the shielding between the cavern and the machine, dedicated to hydraulic network, shall be enlarged to allow line of sights with topographical instruments, linking cavern fiducials marks to the "machine geometry". See [18] and [21].

5.3. INITIAL ALIGNMENT

The method is identical to that used for point 1 and point 5. See § 4.3.

5.4. MAINTENANCE OF THE ALIGNMENT *BEAM ON*

5.4.1. THE REMOTE CONTROL OF ONE INNER TRIPLETS

The method is identical to that used for point 1 and point 5. The equipment installed on the cryostat for this purpose is the same. (see § 4.5.1)

5.4.2. THE RELATIVE ALIGNMENT OF THE TWO INNER TRIPLETS

After the completion of the installation of the experiment, no direct connection in X and Y is possible between right and left tunnels around the experiment. So there is a remote control of one inner triplet with respect to the other only in vertical.

The relative alignment of the left and right inner triplets in the horizontal plane is obtained as follows:

- The measurements made on the geodetic network through the UX cavern when dismantling of the LEP experiment assume that the relative position between left and right is correct.
- The fiducials of the cryostats are periodically measured with respect to the corresponding part of the arc with traditional methods (wire offset measurements, angles measurements, and gyroscopic measurements if needed). The calculation method shall allow the detection of any radial displacement of the global triplet.
- In addition, measurements taken on the reference points sealed in the floor of the tunnel will help to determine ground motion.
- The two lines of sight across the shielding between UX cavern and tunnel shall improve the radial accuracy in the determination of the position of the cavern w.r.t. the "machine geometry". (This improvement has only been accepted regarding point 2, see [18]; regarding point 8, several ways linking the right and left parts of the tunnel are studied, see [26].)

The relative alignment of the left and right inner triplets in the vertical plane is obtained thanks to the Hydrostatic Levelling System. The only difference with CMS and ATLAS case is that the Hydrostatic Levelling System has no UPS gallery dedicated. The constraints and the solution proposed regarding the HLS integration in ALICE cavern are shown in [18], regarding the HLS integration in LHCb cavern are shown in [26].

5.4.3. ALIGNMENT OF THE TWO INNER TRIPLETS WITH THE ARCS OF THE MACHINE

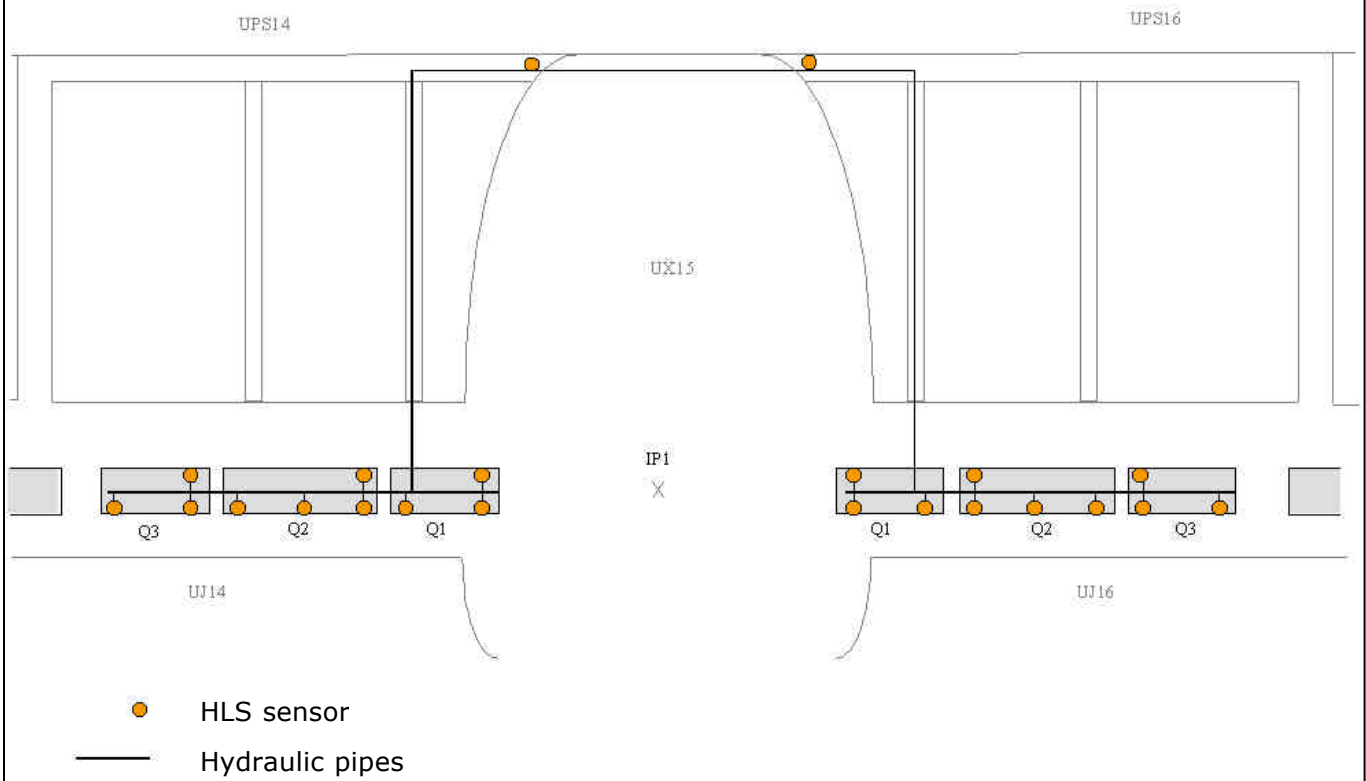
The method is identical to that used for point 1 and point 5.

5.5. MAINTENANCE OF THE ALIGNMENT *BEAM OFF*

The method is identical to that used for point 1 and point 5.

Appendices

Appendix A



Appendix B

